Computer Modeling in the Design and Evaluation of Electric and Hybrid Vehicles
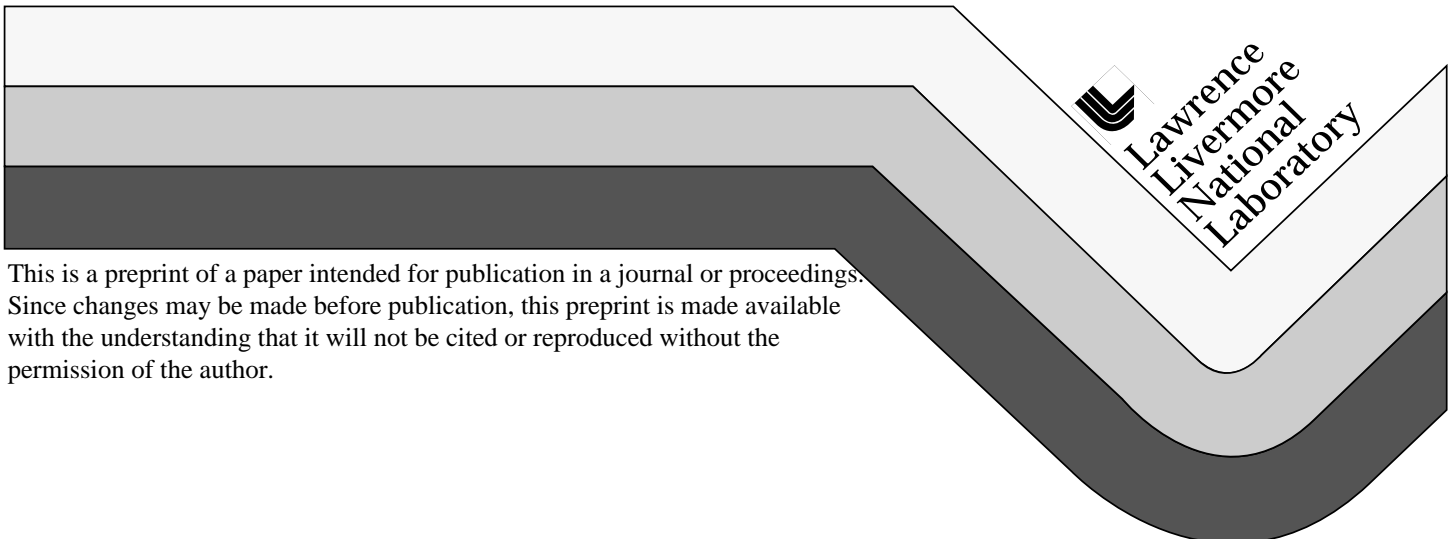
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of Electric and Hybrid Vehicles*

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Key Words: Hybrid vehicles, Electric vehicles, Hydrogen fuel, Vehicle simulation.

Prerequisite Knowledge: Computer science (executing a Fortran program), analysis techniques (plotting numerical results, comparison of simulation runs), vehicle design (some knowledge of components of automobiles).

Objectives: To illustrate the changes in performance and fuel economy that result from the changes in vehicle characteristics, and to show the application of simulation tools to solve current engineering design problems.

Supplies: Computer with Fortran compiler, text editor, graphics plotting software.

Introduction:

Light-duty vehicles (consumer automobiles) are major contributors to urban air pollution and greenhouse emissions. They also consume much of the oil supply to the country, causing oil dependence on unreliable foreign sources.

This demonstration project uses modern simulation techniques to illustrate the important technologies and design variables that an auto-designer would consider in producing a high efficiency, low emissions vehicle. Simulation and modeling techniques use the idea of capturing the relationships between real components of the system with mathematical equations. These equations are then solved on a computer to simulate the behavior or performance of the system under various conditions. Simulations and models are a useful analysis tool for the following reasons:
- To provide insight and understanding of the real system
  - Especially the complex dynamics from the interaction of simple physics
- To predict the performance, given modifications of the system.
- To supplement experimental results
  - Especially when experiments are costly, unavailable or of low fidelity.
- To optimize the performance of the system.
- To develop control or operation strategies of the system.

In the current demonstration project, we focus on many variations of a hydrogen-powered vehicle. The fuel that powers the vehicle is hydrogen gas. When hydrogen is burned in the presence of lots of oxygen (a

lean mixture), the only combustion product is water. There is almost no poisonous carbon monoxide (CO); or carbon dioxide (CO_2) produced, an undesirable greenhouse gas; and very little nitric or nitrous oxides (NO and NO_2), pollutants that cause brown hazes and are very irritating to the lungs.   Furthermore, hydrogen can be produced from renewable sources, such as solar or wind power, thereby eliminating our dependence on oil in the US and on foreign oil. Even more exciting is that when used in a fuel cell or a properly designed combustion engine, the power plant can achieve very high efficiencies, much higher than modern gasoline engines used in automobiles.

The demonstration project also focuses on a particular type of vehicle, the series hybrid vehicle, that has been shown to have a high operating efficiency. When the high efficiency, low emission hydrogen engine is combined with a high efficiency series hybrid vehicle, the result is a vehicle that has nearly zero emissions, performs well, and is highly efficient.

The Series-Hybrid Vehicle with Advanced Energy Storage:

Series hybrid vehicles provide an alternative for obtaining vehicles with high fuel economy. Gasoline engines in conventional cars have a high peak efficiency (32%). However, most of the driving is done with the engine operating at low power conditions, during idling or city driving. At low power conditions, the engine operates well below its peak efficiency, resulting in a lower vehicle fuel economy. Average gasoline engine efficiency has been estimated to be 18% during the urban cycle and 26% during the highway cycle. In a series hybrid vehicle the engine always operates at or near its optimum, without ever idling. Figure 1 shows a series hybrid vehicle. Figure 2 shows schematics of a conventional vehicle power train and a series hybrid vehicle power train. Conventional cars have a direct mechanical link from the engine to the transmission and to the wheels, and therefore the engine operating conditions are set by the vehicle speed and power demands. Series hybrid vehicles do not have a mechanical link between the engine and the wheels; an electric motor provides the tractive power and recovery of energy during braking (called regenerative braking). The engine can be an internal combustion engine (abbreviated ICE), as found in current automobiles; or fuel cells, the power plants of the future. An engine in a series hybrid vehicle operates in an on-off mode. When the engine is running it drives a generator that supplies electricity to both the electric motor and an energy storage system. Batteries or flywheels can be used for energy storage. The storage system supplies electricity to the traction motor when the engine is turned off. Because the storage system uncouples the engine from the wheels, electric power generation is at optimum efficiency. Series hybrid vehicles have a high fuel economy because the engine is both sized closer to the car's average power consumption and operated at the most efficient conditions without idling. As will be shown in this demonstration, series hybrid vehicles are very sensitive to the efficiency of the energy storage system, and consequently, an efficient energy storage system is necessary for obtaining a high fuel economy. Advanced flywheels can provide a high efficiency and are therefore the preferred energy storage devices.

HVEC: The Hybrid Vehicle Evaluation Code:

This demonstration illustrates the application of the Hybrid Vehicle Evaluation Code (HVEC) to hydrogen hybrid vehicles. The analysis describes the operation of series hybrid vehicles, and the sensitivity of vehicle fuel economy to some of the main vehicle parameters. HVEC can be used to analyze all electric vehicles and hydrogen-fueled hybrid vehicles. Vehicle components may include: combustion engine, fuel cell, battery, flywheel, motor, and generator. The present demonstration concentrates on series hybrid vehicles with hydrogen as a fuel, because these have the potential of reaching a very high fuel economy and near-zero emissions.

HVEC is a Fortran computer code that models the performance and emissions of an all electric or hybrid vehicle in response to a variety of operating conditions. The physics included in the code are simple dynamics - a certain amount of energy is required to perform a specified task. The model includes relationships between operating conditions and required performance data, such as various energy losses in the system or emissions. These relationships are obtained from a variety of sources: experimental, more complex computer simulations, or analytical studies. HVEC is one of a broad class of simulation codes that help designers quickly analyze the performance of a system given a variety of competing designs or operating conditions. The results are then used to select the optimal design, to focus on areas of needed improvement, to optimize the operating conditions, or to gain insight into the dynamics of the system. This broad class of simulations codes are called thermodynamic, zero-dimensional, or system simulation codes, and they offer rapid solutions that are accurate within the applicability of the correlations used in the code. Other simulation codes are used to examine more details of the operation of components of the larger system, like the operation of the hydrogen-fueled engine or the flywheel. These "multi-dimensional" codes require fewer assumptions about the dynamics of the system and are often used to provide the system simulation codes with the necessary correlations. An example of these is KIVA, a code developed at Los Alamos National Laboratory for analysis of fluid mechanics and combustion phenomena inside an internal combustion engine [1].

The sequence of processing in the HVEC code is (1) reading the input files that define the vehicle and the performance characteristics of the components, (2) evaluating the performance of the vehicle under specified driving schedules, and (3) producing a list of the results. HVEC runs in non-interactive mode, with all the vehicle and component parameters specified in data files, which can be modified with a text editor. The data file that specifies the hydrogen series hybrid vehicle is titled "4HYBFLY.CAR." This needs to be modified for this demonstration. Other data files used in the program that do not need to be modified are: driving schedule, battery, fuel cell, and motor files (extension names .SCH, .BTR, .FCL, and .MOT). The results of the execution of the program are in data files that have an extension name .DAT. HVEC does not provide a graphic post processor, but the .DAT files can easily be imported in a graphing package.

Procedure for using HVEC :

Start by using a text editor to see the contents of the 4HYBFLY.CAR file. The file contains data for a specific hybrid concept vehicle that has been developed at Lawrence Livermore National Laboratory over the last few years [2,3]. The most important vehicle parameters are listed in Table 1 and in Figure 1. Exit the text editor without modifying the data file, and execute HVEC. When called, the program responds with a list of 8 vehicle configurations that can be analyzed. Choose "engine-flywheel hybrid" by typing 4 followed by the Enter or Return key. The program asks for the names of the vehicle file, and two results files. Press Enter three times to accept the default names (4HYBFLY.CAR, RESULTS.DAT, and SUMMARY.DAT). The program first calculates fuel economy and emissions by running a simulated drive of the concept vehicle over two driving cycles: the urban and highway driving cycles specified in the Environmental Protection Agency (EPA) Federal Test Procedure. Results for the urban and highway cycles are then used for calculating results for the combined cycle. According to EPA rules, the combined driving cycle is defined as 55% urban driving and 45% highway driving. After finishing the simulated drives, HVEC calculates vehicle acceleration performance (time for 0-97 km/h, 60 mph), and hill climbing performance (hill slope in % that the car can climb at a constant 97 km/h, 60 mph). When the program is finished, use the text editor to read the results from the SUMMARY.DAT file. The most important results are listed at the end of the file, and included here in Table 1.

The results in Table 1 indicate that the vehicle has a very high fuel economy, approaching the 80 mpg goal set by the Federal Government through the Partnership for a New Generation of Vehicles. Vehicle engine and motor are specified to meet performance parameters considered acceptable for the general public (capacity for climbing a 6% hill at 97 km/h and 10 seconds for 0-97 km/h acceleration).

Next, the file FLYWHEEL.DAT can be used to illustrate series hybrid vehicle operation. Import the file into a graphics software, and make a plot of the fourth column (state of charge) in the y-axis, vs. the first column (time) in the x axis. Only the results for the urban cycle need to be plotted. Results for the highway cycle follow those for the urban cycle in the file. These can be deleted before making the plot. Figure 3 shows the results. This figure shows flywheel energy storage divided by its maximum capacity as a function of time. Initially, the state of charge is low and the engine is running to charge the flywheel. When the flywheel is charged (at about 130 seconds), the engine is turned off, and the flywheel provides all the energy for accessories and transportation. When the flywheel is discharged again, the engine is turned on to repeat the cycle.

Finally, HVEC is applied to analyze the sensitivity of vehicle fuel economy (combined cycle) to the following vehicle parameters: test weight, frontal area, rolling friction coefficient, flywheel efficiency, and accessory load. This is to determine which of these parameters has the greatest effect on fuel economy, indicating where the greatest efforts should be directed for obtaining high fuel economy vehicles. To do this, start by multiplying the test weight by 0.9 (1272*0.9=1145) and substitute the result as the test weight in the file 4HYBFLY.CAR. Run HVEC and obtain the combined cycle fuel economy from the SUMMARY.DAT file (this can also be read directly from the screen). The result is 33.7 km/l (79.2 mpg). Now, change the vehicle weight in the data file back to its original value, and replace the value of the frontal area by 90% of its original value and run HVEC. Repeat this procedure for all the variables listed above, keeping all variables at their original value, except for the single variable being modified. The fuel economy obtained from these runs can then be used in obtaining the percent change in fuel economy that results from a 10% reduction in any vehicle parameter. The percent change in fuel economy for a 10% change in vehicle weight is:

$$100*(79.2-75.6)/79.2=4.54\% \tag{1}$$

All other percent changes are calculated in a similar way. The results are illustrated in Figure 4. The figure shows the percent change in vehicle fuel economy for a 10% reduction in the given parameters. The percent change in fuel economy due to reductions in mass, area, rolling friction coefficient, and accessories is positive because fuel economy increases when these parameters are reduced. Fuel economy decreases due to reductions in flywheel and engine efficiencies, resulting in negative changes for these variables. It can be seen that fuel economy is most sensitive to engine efficiency and flywheel efficiency (about 10% for a 10% change in these parameters), with smaller changes in fuel economy due to changes in weight, area, rolling friction coefficient, and accessories. The great sensitivity of fuel economy to flywheel efficiency is what makes it necessary to have an efficient energy storage system for series hybrid vehicles to be successful. A typical battery has an efficiency of the order of 70%, which may result in a low vehicle fuel economy. Accessories can increase substantially (up to 3 kW) if air conditioning or heating is required. Under these conditions, accessories would have a great effect on fuel economy.

Suggestions for additional studies:

1. Because the weight of the vehicle is included into HVEC, the importance of using advanced light-weight materials in the construction of the vehicle can be evaluated or the effect of using the vehicle as a light duty truck.

2. Suppose that fuel economy was less important than acceleration. Redo the above study looking at acceleration times.

3. The relative effect of changing the variables (such as the conclusion that the best payoff is to focus development in the proposed study is in the flywheel and engine design) differ under either various designs and operating conditions. Repeat the above study with a different design.

4. Use HVEC to optimize the vehicle transmission. Modify the value of the 1st gear reduction ratio given in the 4HYBFLY.CAR file (numbered 24). Make 11 runs of HVEC for values of the reduction ratio between 200 and 400 at intervals of 20, and keep a record of how the fuel economy changes as the gear ratio changes. A gear ratio will exist for which a maximum fuel economy is obtained. Also, keep track of the acceleration time as these runs are made. Minimum acceleration time (maximum vehicle performance) will not be obtained at the same gear ratio as maximum fuel economy. This is an example of conflicting requirements in vehicle design where a compromise has to be made between optimum performance and optimum fuel economy.

Notes to the Instructor:

1. When modifying the data files, make sure that no additional lines are introduced in the file. The file is read line by line, and if the required information is not found in the exact line, the program may crash or give wrong results. It is recommended that the original files be backed up before modifying to be able to recover from these problems.

2. Make sure to use an ASCII text editor. If a word processor is used, make sure that the files are saved as ASCII text.

References:

1. Amsden, A.A., 1993, "KIVA-3: A KIVA Program with Block-Structured Mesh for Complex Geometries," Los Alamos National Laboratory Report LA-12503-MS.
2. Smith, J.R., 1993, "The Hydrogen Hybrid Option." Proceedings of the Workshop on Advanced Components for Electric and Hybrid Electric Vehicles, Gaithersburg, MD, NIST special publication 860.
3. Aceves, S. M., and J. R. Smith, 1995, "A Hybrid Vehicle Evaluation Code and Its Application to Vehicle Design," SAE paper 950491.

Glossary:

Accessories: Automotive components that are necessary for meeting passenger needs not directly related to transportation. Accessories include air conditioner, radio, powered windows, etc.
Accessory load: Power required to drive all accessories, in Watts. Air conditioning and heating are the accessories that require the most power.

<u>ASCII</u>: Format for storing information in a computer. This format only permits the use of 256 basic characters. This is a basic format that can be read and used in any computer.

<u>Drag</u>: Force exerted on a body as a result of the motion of a fluid around it. For cars, drag is given by the following equation:

$$F_d = \frac{1}{2} C_d \rho A v^2$$

(2)

where C_d is the drag coefficient, ρ is the air density, A is the vehicle frontal area, and v is the velocity.

<u>Drag coefficient</u>: Constant used in calculating drag. See above. It is primarily a function of the shape of the body.

<u>Flywheel</u>: A rotating mass used to store kinetic energy. A flywheel stores energy as its speed increases, and gives up energy as its speed decreases. Advanced flywheels rotate at speeds of up to 80000 revolutions per minute. Energy input and output is done electrically.

<u>Fuel cell</u>: Device that converts fuels into electrical energy through electrochemical rather than mechanical means.

<u>Partnership for a New Generation of Vehicles</u>: A collaboration between the Federal Government and the car manufacturers (Ford, GM, and Chrysler) to develop high fuel economy, low emission vehicles.

<u>Regenerative braking</u>: Braking in which the loss of kinetic energy from braking is stored and subsequently fed back to provide tractive effort. Currently it is only practical in electric and hybrid vehicles where braking can be achieved by using the motor as a generator.

<u>Rolling friction</u>: Retarding effect on a vehicle, consisting primarily of tire and mechanical friction. It is calculated as:

$$F_r = rmg = rW$$

(3)

where r is the rolling friction coefficient, m is the vehicle test weight, g is the acceleration of gravity (9.8 m/s^2), and W is the weight of the vehicle.

<u>Tractive power</u>: Power required to move a car under a given set of conditions.

Table 1. Main parameters and results (fuel economy and performance) for the LLNL concept hydrogen hybrid vehicle specified in 4HYBFLY.CAR.

Vehicle parameter	Value
Test weight, kg (empty weight +136 kg)	1272
Frontal area, m2	2.04
Drag coefficient	0.24
Rolling friction coefficient	0.007
Flywheel turnaround efficiency, %	90
Accessory load, Watts	1000
Engine peak efficiency, %	46
Generator peak efficiency, %	95

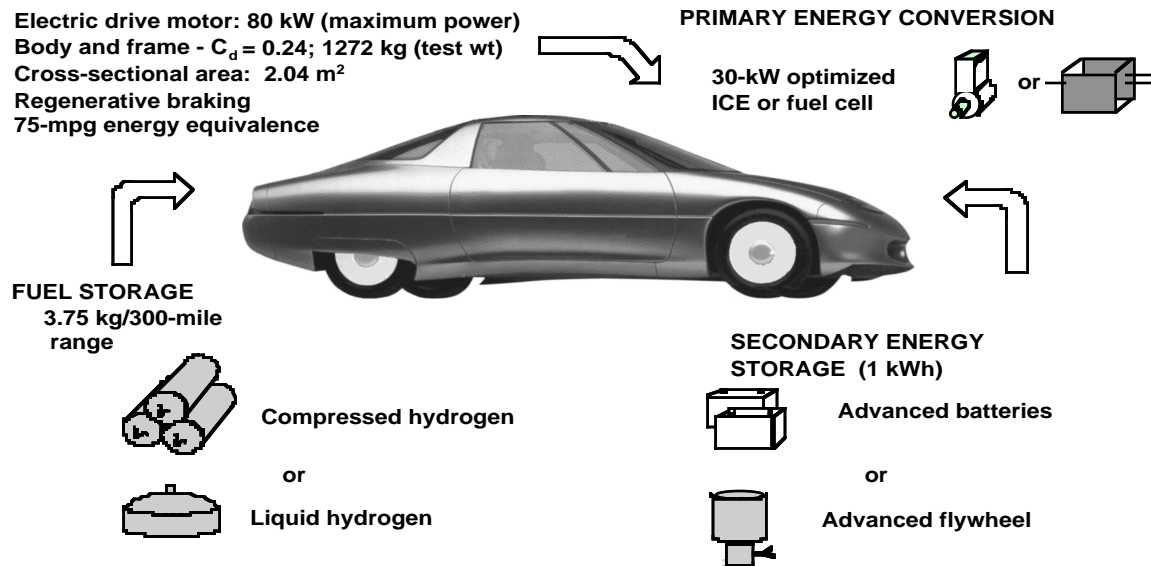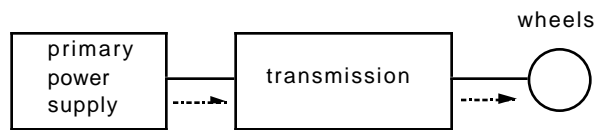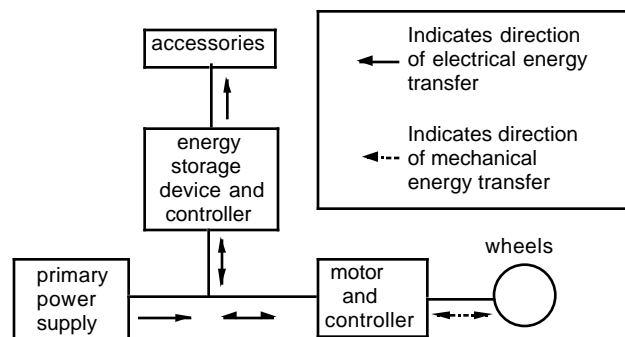| Results	Value
Fuel economy, urban driving cycle, km/l (mpg)	29.3 (69.0)
Fuel economy, highway driving cycle, km/l (mpg)	36.4 (85.6)
Fuel economy, combined driving cycle, km/l (mpg)	32.1 (75.6)
Time to reach 97 km/h (60 mph), seconds	10.0
Climbing slope at 97 km/h (60 mph), %	5.96

Electric drive motor: 80 kW (maximum power)
Body and frame - C_d = 0.24; 1272 kg (test wt)
Cross-sectional area: 2.04 m^2
Regenerative braking
75-mpg energy equivalence

PRIMARY ENERGY CONVERSION

30-kW optimized
ICE or fuel cell

or

FUEL STORAGE
3.75 kg/300-mile
range

Compressed hydrogen

or

Liquid hydrogen

SECONDARY ENERGY
STORAGE (1 kWh)

Advanced batteries

or

Advanced flywheel

Figure 1. Components of a hydrogen series hybrid vehicle, including engine, fuel storage and energy storage device.

wheels

| primary power supply | transmission |

(a) conventional vehicle power train

accessories

Indicates direction
of electrical energy
transfer

energy
storage
device and
controller

Indicates direction
of mechanical
energy transfer

wheels

primary
power
supply

motor
and
controller

(b) series hybrid power train

Figure 2. Schematic of a conventional car and a series hybrid vehicle power train. For the series hybrid vehicle described in this demonstration, the primary power supply is a hydrogen engine, and the energy storage device is a flywheel.
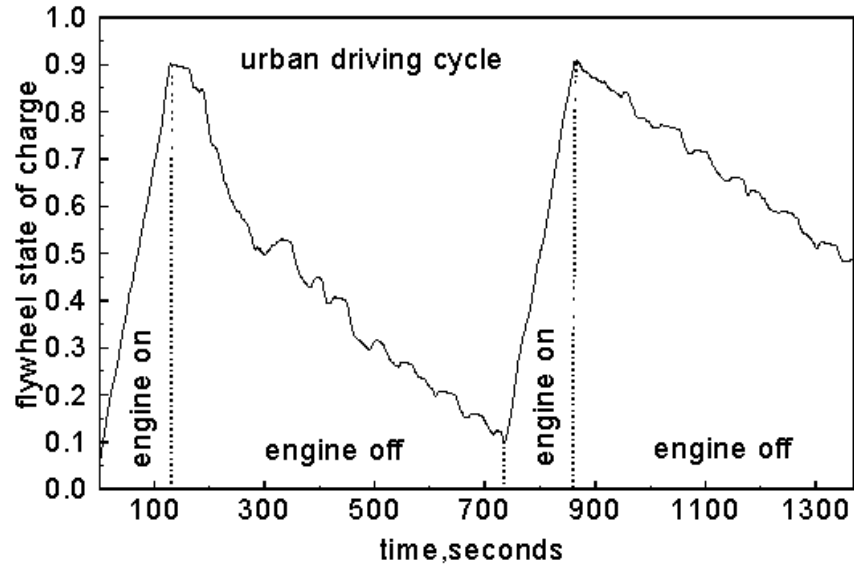
Figure 3. Flywheel state of charge (energy stored in the flywheel divided by the maximum energy that can be stored in the flywheel) as a function of time, for the hydrogen hybrid concept vehicle during the urban driving cycle.
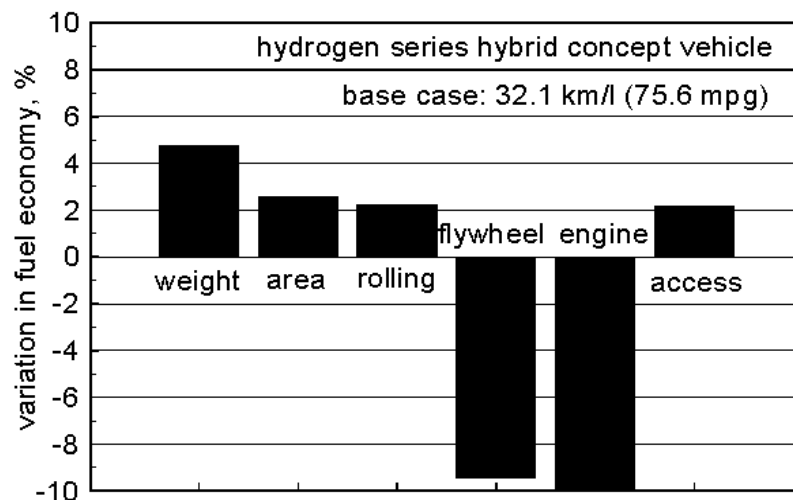

Figure 4. Percent change in vehicle fuel economy for a 10% reduction in the given parameters. The labels in the column represent the following vehicle parameters: weight is the test weight; area is the frontal area; rolling is the rolling friction coefficient; flywheel is the flywheel turnaround efficiency; engine is the engine efficiency; and access is the accessory load.